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THREE-DIMENSIONAL CRACK DEPTH PROFILE ASSESSMENT USING NEAR-FIELD SURFACE ACUSTIC WAVE SIGNAL RESPONSE (Postprint)

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14. ABSTRACT
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Three-dimensional Crack Depth Profile Assessment using Near-Field Surface Acoustic Wave Signal Response

James L. Blackshire, *Member, IEEE*

Abstract—**A method for determining the three-dimensional depth profile of a surface-breaking crack-like feature is presented based on near-field surface acoustic wave signal responses. Three-dimensional finite element models were used to study the forward problem, where the characteristic near-field scattering of a surface acoustic wave incident on a surface-breaking crack was investigated. Experimental validation of the modeling predictions was accomplished using a wedge transducer for surface wave generation and a scanning laser vibrometry system for surface wave detection. The characteristic near-field amplitude response in reflection and in transmission was measured and modeled for flat-bottom, angled, and curved-bottom localized notch features, where a simple linear inversion method was developed, which provided an effective means for characterizing and mapping the three-dimensional depth profile of surface-breaking crack-like features with depths in the micron to millimeter range.**

Index Terms—**Surface Acoustic Wave, Crack Depth Profile, Near Field Scattering**

I. Introduction

In recent years, the need for fully characterizing damage in aerospace systems has become increasingly important. The accurate and reliable quantification of crack length, depth, aspect ratio, and orientation, for example, is needed for condition based maintenance (CBM) assessments of many legacy and future aircraft systems [1]. Ultrasonic sensing represents a key NDE method for 2D and 3D crack characterization, where recent advances in sensing and analysis methods have led to important improvements in both measurement capabilities and accuracies [2-7].

Because they typically reside on accessible surfaces, surface-breaking cracks (SBCs) represent an excellent test case for understanding and advancing 2-D and 3-D crack characterization, where the specific features of a crack can be easily verified [2,8]. In addition, the analytic scattering problem has also largely been solved for surface acoustic wave interactions with surface-breaking cracks, providing a sound technical basis for method development and validation [9-11]. Recent advances in distributed sensing, and point-wise generation/detection, for example, have led to improvements in sensing resolution, where innovative sensing concepts near a crack scattering site can be exploited [11-13].

In the present effort, the use of forward numerical models, point-wise laser interferometric detection, and inverse method development have been combined to provide a means for quantifying the local 3-D crack depth of a surface-breaking crack. Numerical models were used to parametrically study the effect of depth variation on the local reflected and transmitted SAW amplitude levels immediately in front of, and immediately behind, simulated surface-breaking crack features with known depth profiles. A simple linear relationship was observed between the local amplitude ratios and notch depth, where a simple inversion formula was developed, and experimental studies were subsequently used to validate the model predictions and inversion method approach.

II. SAW Scattering from Surface-Breaking Crack

A. Physics of Scattering Problem

The scattering of a surface acoustic wave from a surface-breaking crack has been studied by many researchers and is well understood [1,14-16]. To a large degree, these efforts have focused on the analysis of far-field signals, where in general the reflection/transmission signal behavior is predicted to increase/decrease, respectively, with increasing crack depth. Numerous experimental studies [5,17-19] have verified the basic features of these analytic predictions, with numerical models [2-5] providing additional insight into the problem.

The development of practical and reliable characterization methods still remains a challenge, however, where the complex nature of the scattering process can result in numerous confounding factors involving the spatial and temporal interference of mode-converted, reflected, and transmitted waves [2,18,20]. These interference effects can cause oscillatory behaviors in the far-field response, which can make detailed crack characterization difficult and unreliable. In addition, source variations, transducer coupling differences, and sensor-crack separation distances have also been suggested as causes for the response variability [18,20].

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Recent ultrasonic approaches involving measurements made very near the surface-breaking crack site have suggested that opportunities for enhanced characterization and reliable sizing may be possible [20-26]. Local enhancements of the SAW amplitude near a surface-breaking crack site have, for example, been observed experimentally [13], where the enhancements closely follow the surface crack morphology, providing a means for directly mapping the detailed surface-breaking crack features.

Additional opportunities for obtaining local crack depth estimates have also been suggested [26], where measurement points immediately in front of and behind a surface-breaking, crack-like feature are of interest (Figure 1). In particular, the out-of-plane displacement levels at those two locations vary in a systematic manner with the surface-breaking feature depth. For shallow depths ($d/\lambda_R << 1$), very little energy will be reflected or scattered, with most of the energy being transmitted as R_{T3}. As depths increase, scattering from the front root (S_1) will combine with the incident Rayleigh wave (R_i), with reflected energy from the front face (R_R), and with transmitted energy along the front face (R_{T1}) to create an enhanced displacement field immediately in front of the surface-breaking feature. Forward propagating energy scattering from the tip (S_2) will reach the surface immediately behind the surface-breaking feature to enhance displacements slightly, before decaying as depths increase further. Enhancements of the energy in front of the surface-breaking feature will continue to increase as depths increase until the penetration depth of the SAW begins to approach the feature depth (d). Beyond d/λ_R ~1, reflected and transmitted energy levels are expected to level-out, as incident (R_i), reflected (R_R), transmitted (R_{T1}), and front root scatter (S_1) waves stabilize and combine to produce the enhanced displacement levels immediately in front of the feature, while the transmitted (R_{T2} and R_{T3}) Rayleigh waves and scattered back root (S_4) energies will stabilize and combine to give minimal displacements immediately behind the feature.

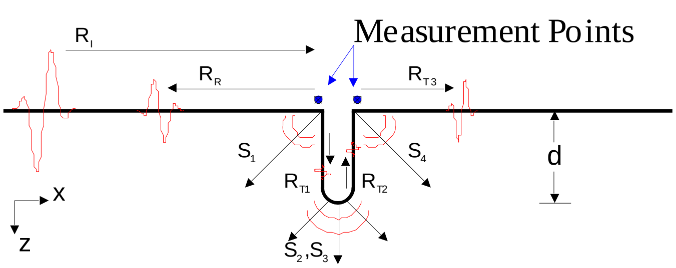

Fig. 1. Schematic diagram of Rayleigh wave (R_i) incident on surface-breaking, crack-like feature with reflected wave (R_R) from front face, scattering from front root (S_1), scattered wave from tip (S_2), scattered wave from back root (S_4), and transmitted Rayleigh waves (R_{T1}, R_{T2}, R_{T3}).

B. *Numerical Modeling Approach and Studies*

A series of 3D-finite element models were used to study the behavior of the Rayleigh wave interactions with surface-breaking, crack-like feature as depicted in Figure 2. The model was developed in a commercially available finite element package PZFlex, which is designed and optimized for elastic wave propagation analysis. The model geometry depicted in Figure 2 was chosen to approximate a ½-penny surface-breaking crack. The overall dimensions of the model included a 10 mm x 10mm cross-section and 20mm length, with the rounded bottom, ½-penny feature located along the top surface at the mid-line along the geometry length. The feature was oriented normal to the top surface and had a width of 25 um, with depths varying from 0 microns on the left and right sides to a maximum depth of 500 microns at the midpoint in the transverse direction.

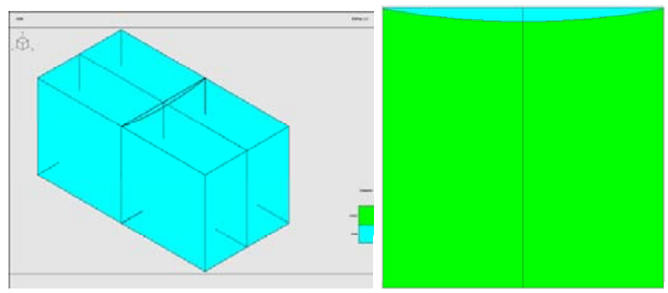

Fig. 2. Schematic of 3D finite element model geometry (left), and cross-section of surface-breaking, crack-like feature (right).

The material properties of aluminum were used for the study with a density of 2700 kg/m^3, longitudinal velocity of 6419.88 m/s, shear velocity of 3039.86 m/s, and Rayleigh velocity of 2996 m/s. A shear-dipole excitation source was applied along the top left surface to generate and propagate a Rayleigh wave along the material surface towards the ½ penny feature. The separation distance between the source and the ½-penny feature (10 mm) was chosen to provide adequate separation of the surface skimming longitudinal wave, bulk waves, and Rayleigh wave, which are all generated using the shear dipole source excitation. Absorbing boundary conditions were applied to the all of the exterior surfaces except for the top surface which was set to be a free boundary. An example of a typical excitation source is depicted in Figure 3, along with its frequency spectrum for a 1.25 MHz excitation.

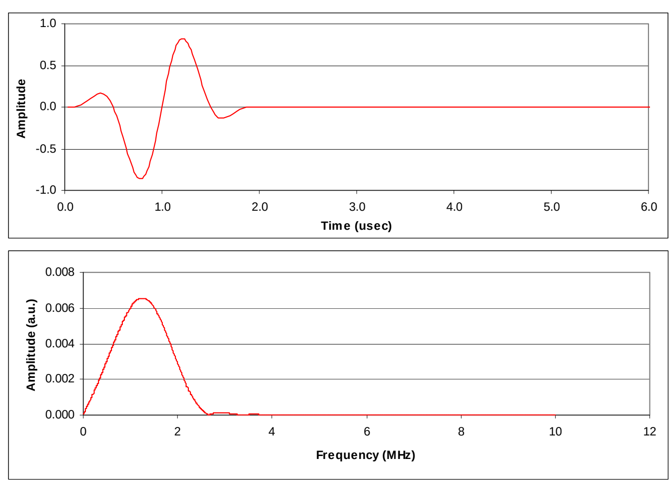

Fig. 3. Finite element 1.25 MHz excitation signal (top), and its frequency

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spectrum (bottom).

Previous research had shown characteristic signal amplitude variations and enhancements which varied with notch/crack depth in the immediate vicinity of the scatter site [4,13,26]. Figure 4 depicts model-based signals extracted from positions immediately in front of and behind a crack-like feature for a SAW frequency of 1.25 MHz (λ_R ~ 2400 um) and for notch depths between 250 um and 450 um (d/λ_R = 0.10 and 0.19, respectively). Reflection amplitudes show an increase of 32% for a notch depth increase from 250 um to 450 um, while a slight decrease in amplitude can be observed for the transmission case.

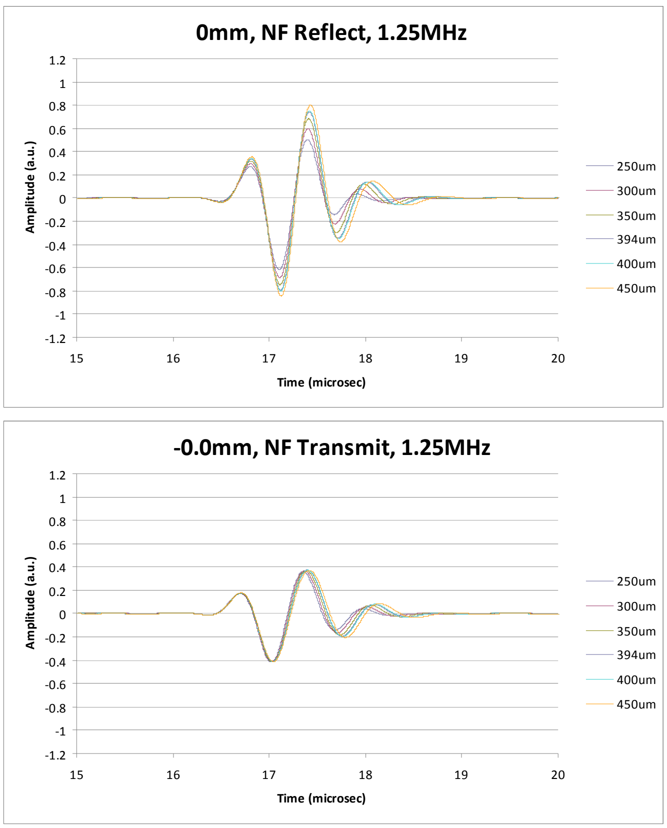

Fig. 4. Out-of-plane displacements for 1.25 MHz SAW frequency, feature depths between 250 um and 450um, and for position immediately in front of notch (top), and position immediately behind notch (bottom).

Figure 5 (top) provides the characteristic curves for the normalized peak-to-peak amplitude response versus d/λ_R for the signals depicted in Figure 4. Relatively complex curves are noticed for both the reflected and transmitted cases, with sharp rising features below d/λ_R = 0.3, a peak occurring between d/λ_R = 0.3–0.5, and a plateau or leveling beyond d/λ_R = 0.8 in both cases. Estimating the depth of a crack-like feature using these curves would be difficult. However, by taking the ratio of the normalized peak-to-peak signals immediately in front of and behind the crack-like feature, the bottom curve in Figure 5 is produced. A linear trend is observed for this ratio plot between the d/λ_R = 0.1–0.8 range, which can be used to estimate the local crack depth using the equation:

$$d = C_1\left(\lambda_R\left(NF_{ratio} + C_2\right)\right) \quad , \tag{1}$$

where λ_R is the SAW wavelength, and Nf_{ratio} = NF_T / NF_R is the ratio of the measured peak-to-peak amplitude levels immediately in front of and behind the notch, respectively.

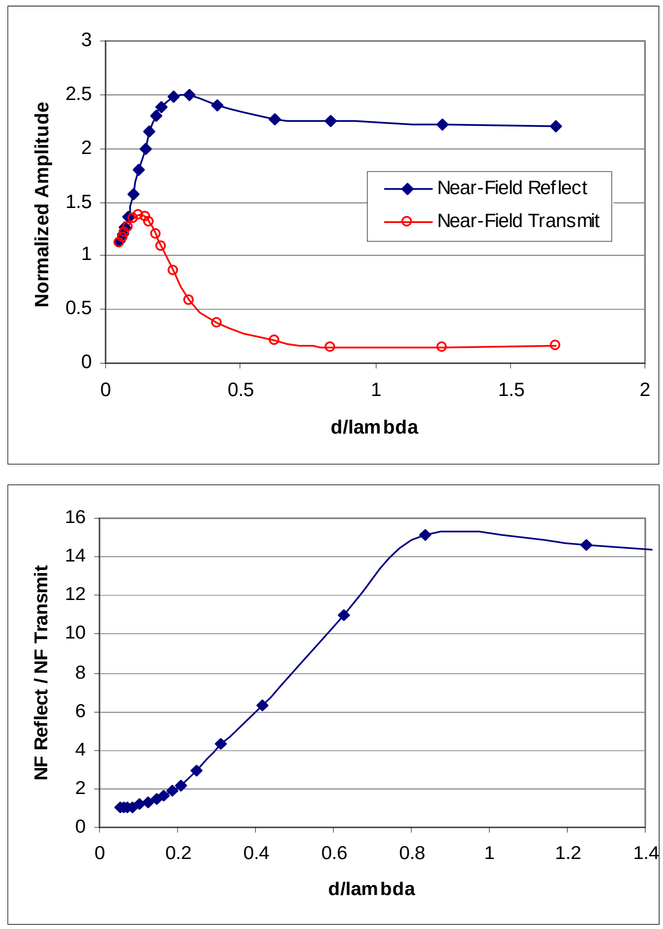

Fig. 5. Normalized peak-to-peak amplitudes for out-of-plane displacements obtained in front of and behind notch for increasing d/λ_R values (top), and ratio of the near-field reflection and near-field transmission plots (bottom).

C. *Surface-Breaking Depth Characterization*

The proposed methodology for estimating the local depth of a crack-like feature uses the simple linear transform equation (Equation 1), where C_1 and C_2 are proportionality constants dependent on the specific crack geometry, λ_R is the Rayleigh wavelength, and $NF_{ratio} = NF_R/NF_T$ is the ratio of the measured displacement amplitudes immediately in front of (NF_R) and behind (NF_T) the feature. Because Rayleigh waves are inherently 2-dimensional in nature, the local depth in the transverse direction can be mapped if spatially-resolved displacement measurements in the transverse direction are made. Figures 8 and 9 provide examples of the predicted depth profile vs actual depth profile for an angled-bottom slot in aluminum, and a model-based ½-penny crack-like feature

as described in the previous sections, where good agreement is observed for the actual depths versus predicted depths.

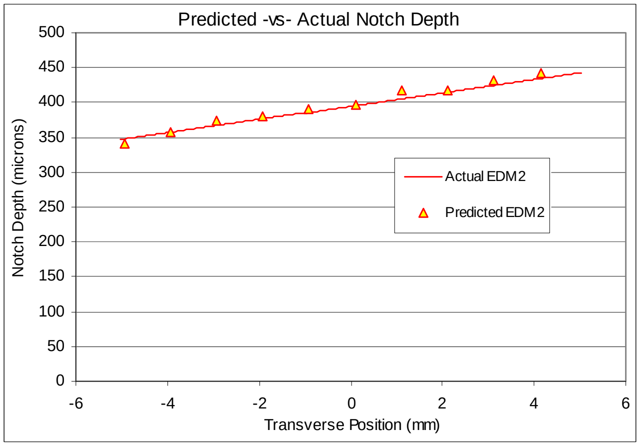

Fig. 8. Plot of predicted versus actual notch depth (bottom) for an angled-bottom slot using measured near-field amplitude ratios and Equation (1).

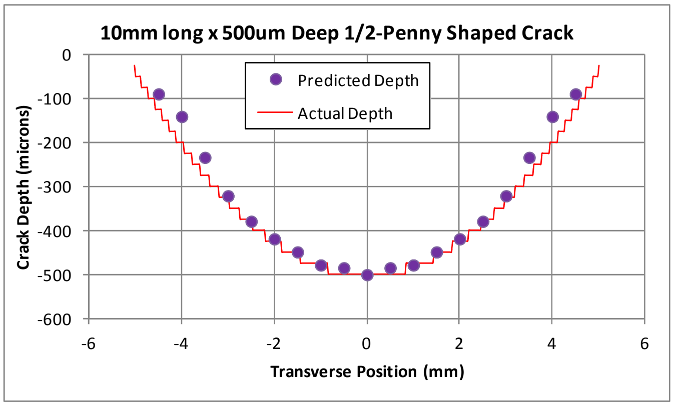

Fig. 9. Comparison of model-based ½-penny crack-like feature with input/actual model profile depth, and predicted depth using model-based near-field amplitude ratios and Equation (1).

III. Conclusion

A method for determining the three-dimensional crack depth profile of surface-breaking crack-like features is presented based on near-field surface acoustic wave signal responses. Three-dimensional finite element models were used to study the forward problem, where the characteristic near-field scattering of a surface acoustic wave incident on a surface-breaking crack was investigated. The characteristic near-field amplitude response in reflection and in transmission was measured and modeled for flat-bottom, angled, and curved-bottom features. A simple linear inversion method was developed, which provided an effective means for characterizing and mapping the three-dimensional depth profile of surface-breaking crack-like features with depths in the micron to millimeter range.

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He is currently a Senior Materials Engineer in the Nondestructive Evaluation Branch, Materials and Manufacturing Directorate of the Air Force Research Laboratory, Dayton, Ohio. He has a broad background in nondestructive evaluation (NDE), non-intrusive diagnostic, and electro-optic methods with particular expertise in ultrasonic NDE modeling and experimental sensing methods, laser-based measurement methods, and terahertz NDE. His current research involves the use of forward ultrasonic models, experimental validation of model predictions, and inversion method development to uncover and mitigate confounding factors (structural geometry and material state variations) for improved detection, location, and quantification of damage in aerospace systems.